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Simulation of Airborne Microbial Droplet Transport

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The framework for a simulation model which describes the dispersion of individual droplets of water containing viable microbes is presented. The model accounts for physical, chemical, biological, and measured meteorological parameters of each droplet at each of many short time steps. Repeating the modeling process for many droplets will simulate a cloud of droplets. The model is compared with the Tulelake, Calif., release in 1988 and found to show very similar patterns of deposition within 30 m (the maximum observation distance of the source. A hypothesis for the survival sequence in the microbe-containing droplets is discussed.

In the past, large-scale aerial dispersal of microorganisms from sources such as evaporative cooling towers (7) and sewage irrigation and treatment plants (20, 21) has been estimated by using atmospheric dispersion models based on temporal and spatial averaging as defined in the Gaussian plume models (8, 9, 14). The averaging process eliminates the detail necessary to adequately delineate the deposition pattern of a microbial aerosol near its source. Models based on estimating the trajectory of many individual droplets, each adjusted for meteorological conditions at each of many small time steps, have been found suitable for this purpose (2, 5, 18, 22).

The purpose of this report is to document a droplet dispersion model for viable microbes that is useful for predicting and detecting with relatively high spacial resolution near-source downwind dispersion patterns.

MATERIALS AND METHODS

Model framework. The droplet model was separated into five submodels: aerosol generation, evaporation, dispersion, deposition, and microbial death. Any or all were computed at each time-step in the trajectory of a droplet. The position of the droplet (D_i) at each time step (δt) in the trajectory was located in a three-dimensional coordinant system, i.e., $D_{i,x,y,z}$, where D is the ith droplet at an x, downwind; y, crosswind; and z, vertically adjusted location. Many iterations of this process can be performed to give a statistically significant cloud of droplets. A general flow diagram of the model is shown in Fig. 1.

Aerosol generation submodel. An aerosol droplet containing microorganisms sprayed from a solution initially follows a trajectory dependent upon the characteristics of the spray apparatus and meteorological conditions. Once droplets are emitted, drag and gravitational force affect droplet vertical location.

Spray droplet characteristics. A simulated microbial aerosol was generated by a simulated sprayer under known pressure through a nozzle with a known droplet size frequency distribution (e.g., see reference 26; W. Yates, personnel communication). The distribution was used to prepare an equation (equation 1) or an overlapping set of polynomial equations where the diameter (d, in microns) of a droplet is a function of its cumulative probability of occurrence (P):

$$d(P) = a_1 + (a_2 \times P) + (a_3 \times P^2) + (a_4 \times P^3) \quad (1)$$

where the a's are coefficients.

Each droplet size was randomly selected by solving equation 1 for a uniformly distributed ($U[0,1]$) series of random numbers generated by the computer system (VAX 750/8600[2], Digital Equipment Corp., Bedford, Mass.). Any droplet smaller than the size of a single bacterium was discarded because we are interested only in the dispersion of bacteria.

The initial droplet velocity at the spray nozzle (v_0) was calculated from equation 2:

$$v_0 = (2g\ F_p/\Omega)^{-2}, \text{ meters per second} \quad (2)$$

where g is the acceleration of gravity, F_p is the spray pressure (kg/m^2) at the nozzle, and Ω is the spray density (kg/m^3) (12, 25, 26). This is the velocity of $D_{i,0,0,0}$ at t_0.

Droplet fallspeed. Airborne particles experience two major forces affecting their vertical location beyond the mean fluctuating wind field; gravity (g) and airdrag (F_D) caused by viscosity of the air and pressure asymmetry about the particle. By assuming a spherical particle shape, the drag force is expressed by equation 3 as:

$$F_D = 6\pi\eta_a r U \quad (3)$$

where F_D defines Stokes drag force, η_a is the dynamic viscosity of air, r is the radius given in microns, and U is the average air flow speed around the particle (meters per second), which is assumed to be the same as w_i in equation 6. Because dynamic viscosity of air varies slowly in the practical temperature range (for details, see reference 23), it is held constant; thus, equation 3 becomes:

$$F_D = 3.39 \times 10^{-10}\ rU, \text{ kilogram meters squared per second} \quad (4)$$

The acceleration (deceleration) (a) due to Stokes drag on a particle is given in equation 5:

$$a = F_D/\text{m} = F_D/(4/3\ \pi\Omega r^3) = 0.8 \times 10^{-5}\ U/r^2, \text{ meters squared per second} \quad (5)$$

The vertical velocity (w, positive up) of a particle for each time step increment is:

$$w_{t+\delta t} = w_t - (0.8 \times 10^5\ w_t/r^2 + g)\ \delta t, \text{ meters per second} \quad (6)$$

where t is time. In order to maintain numerical stability in our model, δt must be:

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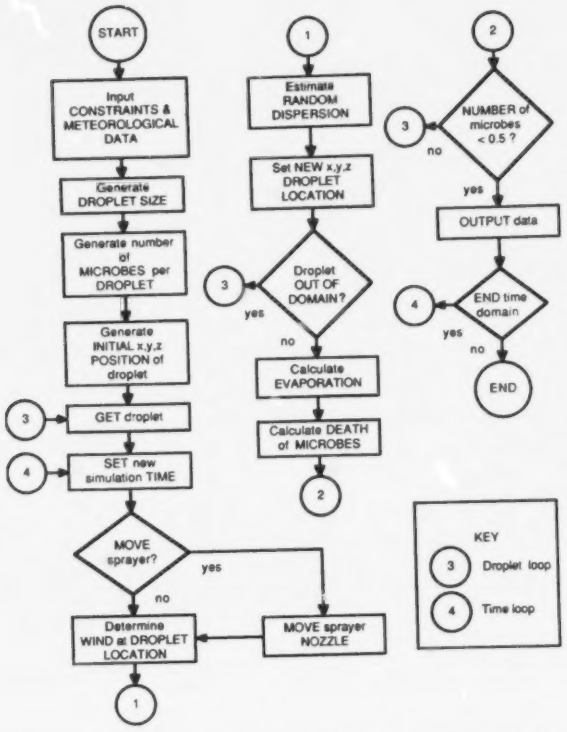

FIG. 1. Flow diagram of the viable droplet dispersion model.

$$\delta t < r^2/0.8 \times 10^5, \text{ seconds} \tag{7}$$

Microbes in droplet. The number of microorganisms in a given size droplet was calculated according to algorithms similar to those used by Kennedy and Gentle (6), with a Poisson distribution when the mean number of microbes in a droplet was less than 50 and a normal distribution $N(\mu,\sigma^2)$ if the mean number of microbes was equal to or more than 50. The mean number of microbes in a droplet was calculated by using equation 8:

$$D_{\text{mo}} = D_{\text{vol}} \times \overline{\text{mo}} \tag{8}$$

where D_{vol} is droplet volume and $\overline{\text{mo}}$ is mean microbial concentration of a uniformly mixed spray solution (number/volume). It is assumed that droplets (greater then the size of a bacterium) could contain at least one bacterium.

Evaporation submodel. Evaporation (or condensation) of droplets takes place when the environmental vapor pressure (p) is lower (or higher) than the vapor pressure at the droplet surface (p_D) and will have significant effects on droplet drift as well as survival of contained microorganisms.

The vapor pressure at the surface of a droplet is dependent upon the solvent (assumed to be water in our model), solute concentration (assumed to be nil), temperature (T), and curvature of the droplet surface, i.e., the Kelvin effect. Equation 9 defines evaporation (17):

$$r_{t+\delta t} = \{r_t^2 + 2[(S-1)/(A+B)]\delta t\}^{-2} \tag{9}$$

where

$$S = \text{supersaturation ratio} = p/p_D \tag{10}$$

and p can be calculated from the ambient relative humidity and temperature, and p_D is saturation vapor pressure for a curved surface of radius r given as (11):

$$p_D = p_s\,[1 + (a/r) - (b/r^3)] \tag{11}$$

We also assume that the temperature of the droplet is the same as that of the ambient environment.

In equation 11, a/r represents the curvature effect of the droplet surface vapor pressure (hence increased curvature increases the vapor pressure and, consequently, evaporation rate) and b/r^2 represents the solute effect, which decreases the vapor pressure with solute concentration increase, where

$$a = 2\sigma/nk_BTr \tag{12}$$

and σ is surface tension of water, n is number of water molecules in droplet, k_B is the Boltzman constant, and T is absolute temperature and

$$b = \frac{\text{number of salt molecules (or ions) in the droplet}}{\text{number of water molecules in the droplet}} \tag{13}$$

In the present model, solute effect is not included due to the uncertainty in the salt (or ion) content in the droplet.

The A and B terms in equation 9 are:

$$A = (L_v\,\Omega_v)/(K_tT) \times [(L_v/R_vT)-1] \tag{14}$$

where L_v is the latent heat of vaporization set at 2.5×10^6 J/kg, Ω_v and Ω_L are the densities of water vapor and liquid, respectively, at temperature (T), K_t is the thermal conductivity of air set at 2.4×10^{-2} J/m s °K, and

$$B = \Omega_L\,TR_v/p_sd_w \tag{15}$$

where R_v is the gas constant for water vapor, p_s is the saturation vapor pressure of a planar water surface at temperature T, and the diffusivity of water vapor (d_w) in the air is (developed from reference 4):

$$d_w = 0.211 \times (T/T_0)^{1.94}\,(p/p_0)^{-1} \times 10^{-4}, \text{ meters squared per second} \tag{16}$$

where $T_0 = 273$°K and $p_0 = 1013$ mb.

The effect of microorganisms in a droplet on the droplet evaporation rate was calculated with the following special assumptions: (i) the microorganisms are uniformly distributed in the droplet; (ii) no active or passive migration (Brownian motion) to the droplet surface occurs; (iii) once the microorganism is at the surface, it remains there; (iv) there are no hydrophilic or hydrophobic interactions between the droplet and microbe; and (v) only the microorganisms present in the vicinity of the surface of a droplet act to reduce the effective evaporation area. The calculations for the effect are based on the number of microbes in the outer shell of the droplet, which is one organism diameter thick (equation 17), times the projected area of the microorganism. The ratio of this area to that of the droplet surface is termed the evaporative surface reduction ratio (equation 18) and is set to reduce the calculated evaporation rate.

$$\text{Number of microbes per unit volume in shell} = 4/3\,\pi\,(r^3 - [r-d]^3) \tag{17}$$

$$\text{Evaporative surface reduction ratio} = \frac{\text{(number of microbes in shell} \times \text{microbe projected area)}}{\text{droplet surface area}} \tag{18}$$

where r is the radius of a droplet and d is the length of a cylindrical bacterium.

As the droplet evaporates, r gets smaller and more of the droplet surface is filled by microorganisms; consequently, the water evaporation rate of the droplet approaches that of the microorganisms. In order to account for intercellular

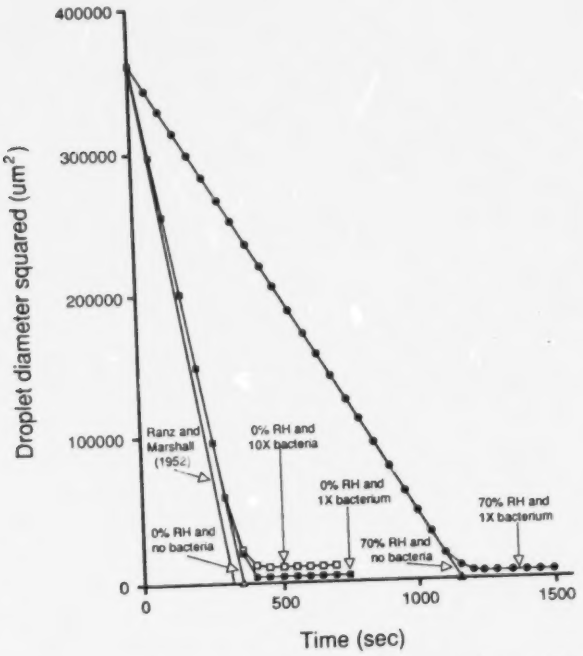

FIG. 2. Simulated water evaporation from bacteria containing (1× = 3 × 10^8 CFU/ml) 600-μm-diameter water droplets in an atmosphere of 0 or 70% RH and 25°C.

water, only 90% of the droplet water was allowed to evaporate. More detailed treatment of intracellular water requires more information not now available.

For purposes of minimizing computational time, several of the variables in the evaporation formulation can be set to constants, including air viscosity, air density, latent heat of vaporization, diffusivity of air, and density of water. These variables show relatively small variations for a normal temperature range.

Output from the simulated evaporation model described above is shown in Fig. 2, where it is compared with the observation data of Ranz and Marshall (17). The figure shows the marked effect of relative humidity (RH) on the longevity of airborne droplets, increasing approximately 400% from 0 to 70% RH. Finally, the graph shows how droplet-contained bacteria might not appreciably affect droplet evaporation until almost all of the droplet water had evaporated and the agglomerated bacteria or droplet nuclei were left. At this point the survival of the agglomerated bacteria might depend on such unknowns as the water evaporation rate, the position in the agglomerate, and the life-sustaining water content of the bacteria.

Dispersion submodel. The dispersion of a droplet in the coordinate system is the summation of wind direction and wind speed alterations at each of many small time steps. Many such droplets would form a cloud. Droplets are assumed to be passively carried by the mean wind.

For a short time internal (δt), the positional change of the droplets in one dimension (x) from the initial position ($D[0]$) to the final position ($D[t]$) may be calculated from equation 19:

$$D_{i,x}(t) = D_{i,x}(t - \delta t) + \mu\, \delta t \tag{19}$$

where the total speed, μ, is the sum of a mean ($\bar{\mu}$) and turbulent component, μ':

$$\mu = \bar{\mu} + \mu' \tag{20}$$

The turbulent component is the summation of a correlated component, the first term in equation 21, and a random component:

$$\mu'(t) = \mu'(t - \delta t)R(\delta t) + \mu'' \tag{21}$$

where the random component μ'' is assumed to have a Gaussian distribution with a zero mean and variance of $\sigma^2_{\mu''}$, equation 22:

$$\sigma^2_{\mu''} = \sigma^2_{\mu'}[1 - R^2(\delta t)] \tag{22}$$

where $R(\delta t)$ is the correlation coefficient of wind speed for the time lag δt. The exact value of $R(\delta t)$ is not available from the data, and $R(\delta t) = 0$ is used for the present time. This value is not zero in general and must be determined from the observed wind data. We also assumed that the correlation coefficient for different wind components (u and v, for example) are zero for all δt.

Repeat calculations to position droplet in the y and z directions.

The droplet motion dynamics are detailed by Hanna et al. (3) and van Dop et al. (22).

Microbial death submodel. The death of airborne microbes has been shown to be functions of at least the atmospheric environmental variables temperature, relative humidity, solar radiation, and time (1). Laboratory measurements of airborne microbial death rates as a function of these variables have been used to prepare descriptive death models that can be adjusted for changes in the environmental variables at each time step (δt) in dispersion models (8, 9, 14). In general, these models simulate the die-off of a population of microorganisms through time under defined environmental and biological conditions (equation 23).

$$N_{\Sigma\delta t} = N_0 \times \text{death rate function} \tag{23}$$

where N_0 is the initial number of bacteria in a droplet, $N_{\Sigma\delta t}$ is the number of surviving microbes from the initial population (N_0) to the time $\Sigma\delta t$, $\Sigma\delta t$ is the sum of the time increments, and death rate function is f(temperature, RH, solar radiation, $\Sigma\delta t$, etc.).

How well these models fit the survival of airborne microbes under natural conditions is problematical. It would be expected that processes other than those mentioned would affect survival under field (as well as laboratory) conditions. Some of these factors include the number of solute microbes in a droplet and how they compact during evaporation of the solvent and the sites, rate, and quantity of bound-water loss (24) and unbound-water loss (evaporation) (13) from the clumped cells. More accurate estimation of death rate for different microorganisms would require very specific, controlled experiments.

Tulelake example. On 28 May 1988, from approximately 0700 to 0710 and 0720 to 0730 at the University of California Agricultural Experimental Station at Tulelake, Calif., two *Pseudomonas syringae* Ice$^-$ recombinants were hand sprayed onto 16 areas randomly located among four rows in a potato field (32 by 55.5 m) (Steven Lindow, personal communication). Local meteorological conditions of wind speed and direction were electronically recorded at one location 1, 2, 3, and 10 m above the ground every 2 min from 0600 to 0900. RH, temperature, and solar radiation were also recorded.

Microbiology. (i) Culture. Details of the culture, sprayout, and sampling procedures are given by Seidler and Hern (19)

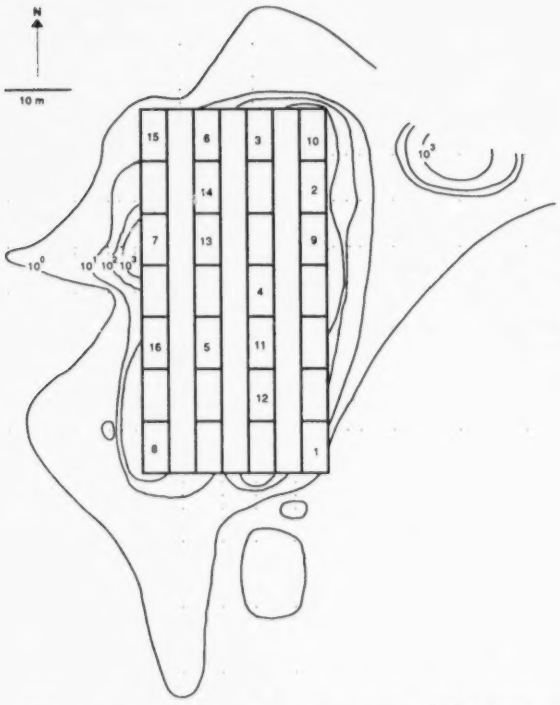

FIG. 3. Diagram of Ice-*P. syringe* sprayout design pattern and deposition map about a potato field (large rectangle) at the University of California Experimental Station, Tulelake (11; Lindow, personal communication). Numbers in small rectangles represent the site and order of the sprayout. Sites 1 through 8 were sprayed from 0700 to 0710 and 9 through 16 from 0720 through 0730 h. Isopleths are scaled in CFU/150-mm petri dish, which are to scale and shown in position as small dots on the map.

and Lindow et al. (11). Briefly, *P. syringae* TLPde11 and Cityde11b were grown on King B agar containing 100 μg each of rifampin and benolate per ml. Cells were harvested and suspended in sterile distilled water to a concentration of 3×10^8 CFU/ml. Four liters of each strain suspension was applied to the plants with a CO_2-pressurized, hand-held sprayer equipped with a Tee-jet 8004 nozzle operated at 2,800g/cm^2. The nozzle emitted spray 15 to 20 cm above the plants. The total number of bacteria sprayed was approximately 1.2×10^{12} CFU.

Spray-drift samples were collected in 90-mm gravity plates of King B agar exposed on the ground for the duration of the sprayout. The plates were arranged in an array radiating out from the spray area as shown in Fig. 3. Exposed plates were incubated for 5 days at 28°C, and colonies were counted.

(iii) Death rate function. There is little information available to prepare a death rate model as a function of ambient temperature, RH, solar radiation, and time, particularly shortly after atomization, for *P. syringae*. Except for the lack of solar radiation, the only data that meet these criteria were measurements made by Poon (15, 16) for *Escherichia coli*. He evaluated the death rate constants (k) from 20 to 80% RH at 20 to 50°C over four time periods: 0 to 0.5 s, 0.5 to 4.5 s, 0 to 2 h, and 2 to 4 h. The constants for each time interval were calculated by using equation 24:

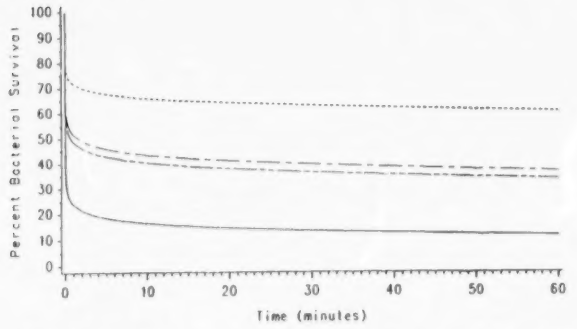

FIG. 4. Simulated die-off of *E. coli* after aerosolization for 20°C at 20 (- - —) and 80% (- - - -) RH and for 50°C at 20 (—) and 80% (- —) RH (as described in references 15 and 16).

$$N(t) = N(t = 0)\, e^{-k(t)t} \quad (24)$$

where $N(t)$ is the number of survivors after time t in a droplet and $N(t = 0)$ is the initial number of organisms at $t = 0$ in a droplet.

A time-dependent death rate constant $K(t)$ for the entire duration of Poon's four time measurements was fitted by a multiple variate general linear model (GLM) (SAS Institute Inc., Cary, N.C.), assuming k for each temperature and RH at the midpoint of the measurement interval. Equation 25 is the death rate model as a function of temperature, RH, and time for *E. coli*. By using this function, simulated survivors over time in an airborne population of *E. coli* can be shown (Fig. 4). The function describes a very rapid initial die-off of airborne bacteria that increases directly with temperature and decreases inversely with RH and directly with time.

$$\log_{10}(K[t]) = -0.22844 - 0.901407 \times \log_{10}(\text{time [min]}) + 0.00997 \times \text{temperature (°C)} - 0.0056 \times \text{RH (\%)} \quad (25)$$

where $K(t)$ is the death rate constant at time t after spray initiation. Interactive terms in the fit analysis were found to have an insignificant (<1%) effect.

Computer program outline. A flow diagram describing the viable droplet dispersion model algorithm whose component parts were described above (Fig. 1) was run in FORTRAN on DEC VAX 785/8605 cluster computer. For the Tulelake case, we assumed that the particles sprayed during the time interval δt were randomly distributed in the spray domain centered at (x_t, y_t), which represents the (x,y) coordinates of sprayer nozzle. By using inputs with known results, the program was checked for proper simulation of nozzle particle size frequency distribution (Fig. 5), wind speed and direction effects, σ^2_μ, sprayer location (e.g., compare actual spray pattern in Fig. 3 with simulated patterns in Fig. 7 at 15 and 30 min), deposition pattern as a function of particle size, and evaporation effects (Fig. 6). This is a very small fraction of the actual number of droplets in the sprayout. In all simulations, 3×10^5 droplets ≥2.0 μm were processed. Droplet characteristics for the Tee-jet 8004 nozzle were obtained from Wesly Yates (Department of Agricultural Engineering, University of California, Davis) and were used to generate a descriptive equation for the droplet size frequency distribution (Fig. 5).

Wind field calculation. To calculate particle locations, particles were assumed to be passively advected by the wind

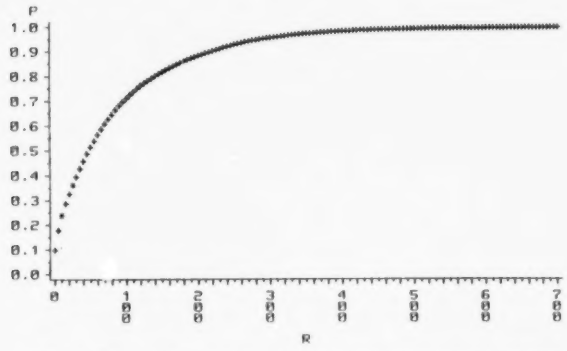

FIG. 5. Cumulative droplet size (R = diameter in μm) probability (P) distribution for 8004 Tee-jet spray nozzle operated at 2,800 g/cm^2, computed from polynomial equation fit of measured droplet size frequency distribution furnished by W. Yates (personal communication). R is calculated from 0.5 to 700 μm.

field about the spray site. Hence, estimation of the typical wind field is required to get dependable estimates of particle dispersion.

The typical wind field was prepared by passing the wind speed data through a five-point weighted running average filter twice (equation 26). The filtering procedure was performed to fill in any missing data and to remove any bad observations, but it also eliminated gusts, which can cause wider dispersion of the droplets.

$$a_1 = \alpha_1 a_{i-2} + \alpha_2 a_{i-1} + \alpha_3 a_i + \alpha_4 a_{i+1} + \alpha_5 a_{i+2} \quad (26)$$

where a_i is the weighted average wind speed at the ith measurement time and $\alpha_1 = \alpha_5 = 0.1$, $\alpha_2 = \alpha_4 = 0.2$, $\alpha_3 = 0.4$ was used.

Next, the wind direction data was divided into east-west (u) and north-south (v) components by equations 27 and 28:

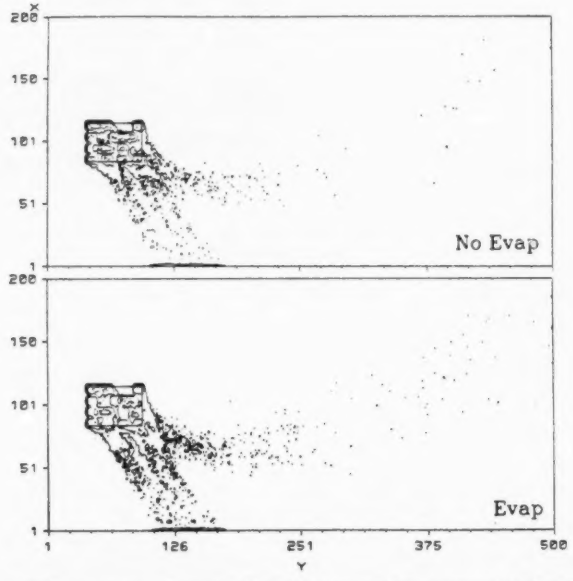

FIG. 6. Maps of simulated particle deposition patterns with and without functional evaporation subroutine (axes in meters; north is left).

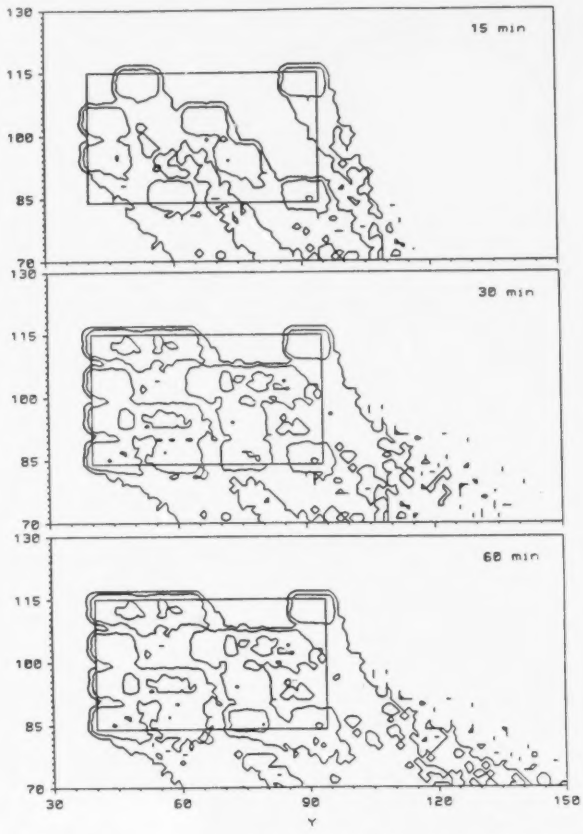

FIG. 7. Large-scale maps of simulated deposition patterns 15 (top), 30 (middle), and 60 (bottom) minutes after spray initiation at Tulelake, Calif. (axes in meters; north is left).

$$u = -V \times \sin \theta \quad (27)$$

$$v = V \times \cos \theta \quad (28)$$

where V is the wind velocity and θ is the wind direction measured in a clockwise direction from north (= 0 or 360°), with westerly and northerly components taken as positive values. The filter in equation 3 was again applied twice for each of the v's and u's to remove any error involved in the wind measurements. Initially, any missing wind measurements were assigned the average value of adjacent measurements. A practical application of the model would be to prepare a strategy to limit the downwind drift from the sprayout.

RESULTS

On a quiescent early summer morning at Tulelake, Calif., gravity plates exposed during and immediately after the sprayout of a polydispersed aqueous aerosol of *P. syringae* showed a pattern of deposition about the source (the large rectangular outline in Fig. 3), with three and possibly four downwind deposition plumes. Two of the plumes emanated from the west side toward the southwest, as would be expected from a northeast wind (top, Fig. 7); one emitted from the east side toward the northeast, as expected from a southwest wind; and one vague plume extended toward the

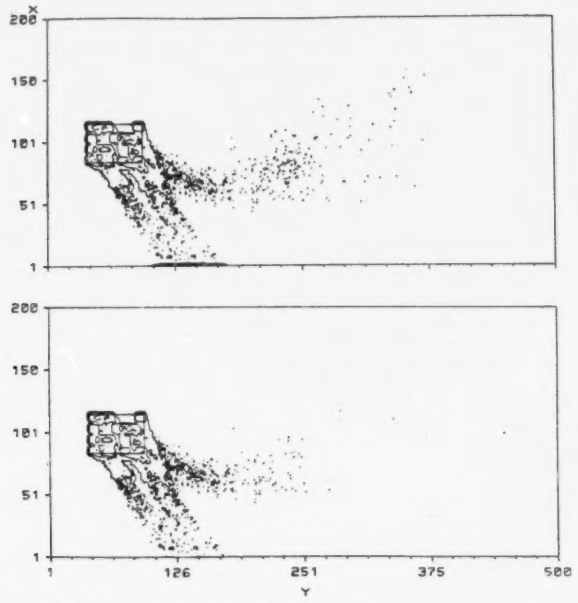

FIG. 8. Maps of simulated deposition (bottom) and airborne plus deposition (top) patterns 45 minutes after spray initiation at Tulelake, Calif. (axes in meters; north is left).

south. During the observation time, the wind shifted from a relatively strong northeast wind (0.32 to 0.94 m/s) to a weaker, erratic southwest wind (0.05 to 0.80 m/s). Except for the easterly plume, the wind conditions would account for the plume patterns. At the time of the wind shift, the simulated sprayout had ceased, but the aerosol droplets produced had progressed far downwind. This downwind progression is shown in Fig. 8, where the southern plume has a more easterly dispersal pattern. It is thought that the mathematical wind-filtering procedure obscured the earlier southwesterly episodes that might have occurred during the sprayout event. More frequent wind measurements would have prevented this loss.

DISCUSSION

There are two general uses for microbial dispersion models: (i) to predict prior to release where microbial droplets might disperse, and (ii) to determine where microbial droplets have dispersed after release. The predictive models have been the focus of past research and are the Gaussian type used in large-scale systems, while determinative models are undergoing development and represent the aerosol-particle type used in small-scale (and large-scale) systems. The particle type also can be used for prediction if representative wind, temperature, and humidity are known. In this case, results are similar to the Gaussian plume model.

The effect of simulated water evaporation from a droplet containing bacteria is an important factor in the deposition process. This is shown in Fig. 6, where droplets are deposited further downwind in the simulation when evaporation is allowed to occur than when it is not allowed to occur. The mechanism explaining this effect in the simulation is that as water evaporates, the resulting evaporate or droplet nuclei form a small particle which is more easily kept aloft by turbulent wind and are advected downwind.

Also, a result of water evaporation from the droplets is that droplets originating with many microbes will form the larger residue droplet nuclei. Further, it is hypothesized that as droplet water evaporates, cells, which are thought to have a lower water vapor pressure (e.g., due to lipid-containing cell membranes), may be present in the droplet air-water film, lowering the overall droplet evaporation rate. Carrying the argument further, it is hypothesized that as the cells agglomerate or form a protective shell configuration during evaporation, the outermost cells would dry to a critical (life-sustaining) water content before those cells deeper in the agglomerate do. From this, it might be expected that those relatively large droplets that originate with the most microbes would contain at least one deeply embedded viable microorganism for the longest period of transport time downwind. Thus, the larger droplet nuclei presumably will have more surviving microbes over a longer time. This is consistent with observations made by Lighthart (10; unpublished data), in which most of the airborne bacteria-containing particles are much larger than the bacteria they contain, e.g., $\geq$9.2 μm in diameter. There is, of course, a limitation to this idea. If the original droplet is large enough, gravity and air drag will quickly cause its deposition before it can evaporate.

Because of monetary constraints, the number of simulated droplets used in this simulation is too small to allow a quantitative comparison against real-world observations, e.g., approximately 10^{12} droplets were disseminated, but only 10^4 were simulated. Thus, relatively large droplets with many bacteria occur so rarely that they probably were not generated during the simulation. For reliable comparisons, we need to simulate more droplets.

A practical application of the model would be to prepare a strategy to limit the downwind drift from a sprayout. For example, simulated droplets generated from a sprayer can be divided into those whose trajectories intersect the ground surface; those $>$50 μm in diameter, about 50% of the droplets from the simulated nozzle; and those $<$50 μm in diameter, whose trajectory contributed to the dispersion cloud. The problem is reduced to minimizing the generation of dispersable droplets of $<$50 μm by selecting the nozzle type and adjusting its operating performance by adjusting sprayer pressure and liquid consistence and spraying when small droplets (e.g., $>$50 μm) will quickly evaporate and the contained microorganisms will die. Low atmospheric relative humidities (23) and high solar radiation, temperature, and atmospheric pollutants (10) would tend to cause the death of airborne microbes most rapidly. The microbes in the large drops would experience minimal mortality because of the short time they are airborne before striking their target surface.

A practical application of the model would be to locate the sample site dependent upon the predicted deposition pattern generated by the model with known input meteorological conditions at the application site and death rate constant of the applied agent.

There are several areas where research is needed to provide a more reliable model. The physical, chemical, and meteorological properties characterizing water droplets in air are well enough known to allow the development of a random-walk model to simulate the dispersion of water droplets containing viable microbes, but the most pressing need is information necessary to predict near-source survival dynamics of airborne microbes, e.g., effects of microbes on the water evaporation of a droplet, water evaporation rate from microbes, critical water content of

microbes, microbial positional effects on their survival in a droplet, and solar radiation effects on airborne survival. Finally, it is important to know if and how soluble products from microbes in the droplet affect droplet evaporation and microbe survival.

Dispersion patterns estimated by the current model depend heavily on the input wind data. Gusts which last less than a minute can take many droplets in directions much different from that of the mean air flow. Hence, more frequent and accurate wind observations can greatly improve model results. The need for improved wind observations is indicated by comparing the observed data map in Fig. 1 against the model results. While the observed data shows a wide area of detection at the northern edge of the spray site, wind data showed no significant wind from the south.

A future use of the model can be seen in which the model is used in real time to predict the aerosol dispersal of a biological mitigant sprayed out but not contaminating a field where an experimental bacterium has been applied. An example is the containment of uninfected bacteria within a continuously generated phage aerosol that forms a closed-ended downwind containment about the bacterium application area.

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